Modeling of Hurricane Impacts

Interim Report 4
March–August 2007

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14. ABSTRACT

This fourth interim report describes ongoing development and validation of the XBeach model as part of the MORPHOS project and other activities over the period March-August 2007 (period extended due to late approval to continue)

15. SUBJECT TERMS Surf zone, swash, overwash, wave groups, wave propagation, morphology, dune erosion

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Contents

Abstract

This interim report describes activities in the first quarter of the second year of the project 'Modeling of Hurricane Impacts'. Due to late approval to start, the work was carried out over the period March-August 2007. Three main lines of work are described in this report, viz. dissemination of model and results, further model improvements and testing.

1   Introduction

This report is the fourth interim report of the project 'Modeling of Hurricane Impacts', contract no. N62558-06-C-2006, which was granted by the US Army Corps of Engineers, Engineer Research and Development Center (ERDC), European Research Office and administered by FISC SIGONELLA, NAVAL REGIONAL CONTRACTING DET LONDON, SHORE/FLEET TEAM. This report covers the activities over the period of March 1st, 2007 to September 1st, 2007. This period is longer than the usual 3 months since there has been a delay in awarding of the item 1001; the original due date was June 1st, 2007.

The project is being carried out by Prof. Dano Roelvink of UNESCO-IHE (Principal Investigator), Dr. Ad Reniers (Delft University and University of Miami), Jaap van Thiel de Vries of Delft University of Technology and Dr. Ap van Dongeren, Dirk-Jan Walstra and Jamie Lescinski of WL | Delft Hydraulics.

The various activities over the period of March-August 2007 are outlined in Chapter 2. In Chapter 3 we outline plans for the coming period.

2 Activities March–August 2006
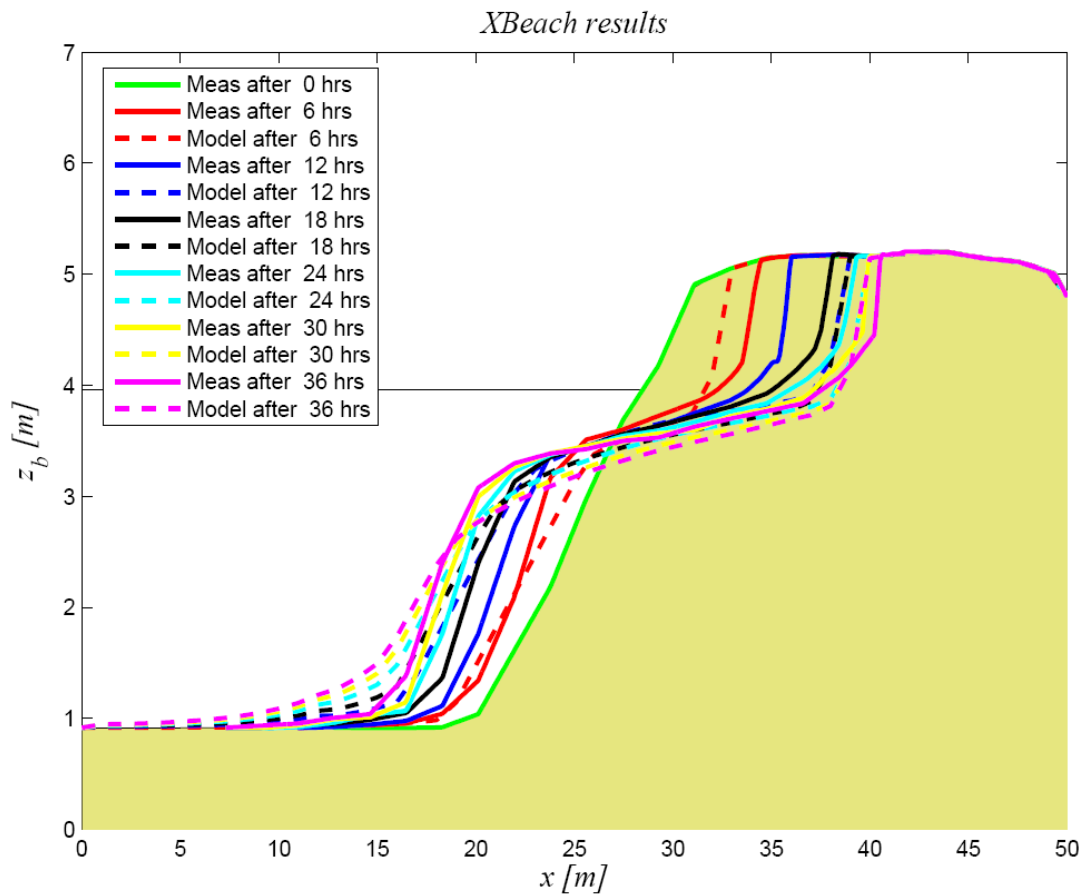
2.1 Dissemination of XBeach

At this stage, for this public-domain model to obtain a broad acceptance, user-base and developer-base, it is very important to spread the message widely and to have a group of external researchers test it for a range of applications.

Presentation of results on conferences and workshops

Dano Roelvink presented the results obtained over the first year at a Gordon conference on Coastal Oceam Modeling in New London, NH in June 2007 and at the 25th anniversary symposium of the Netherlands Centre for Coastal Research (NCK), also in June. Furthermore, he sent in an abstract for the 10th International Workshop on Wave Hindcasting & Forecasting & Coastal Hazard Assessment to be held in Oahu in November, during which there will also be a Morphos meeting. The abstract was accepted, see appendix 1. Also, an abstract was sent in to ICCE 2008 (see appendix 2).

Testing at ERDC

Brad Johnson at ERDC has started testing XBeach against data sets obtained at Oregon State University's large wave tank, in close contact with our group. Overall results look promising, though discrepancies are found for individual events. The discussion focuses on the reproduction of the exact wave conditions in this tank in the XBeach model. Some very preliminary results are presented in the Figure below

Comparison between large-scale erosion tests at OSU's large wave tank and XBeach. Preliminary results, courtesy of Bradley Johnson, ERDC.

Collaboration with ECORS group, France

A group of French universities led by the University of Bordeaux, plus several ones from UK, Australia and the US are planning a very large field experiment on the Atlantic coast of France in March 2008. In this project, sponsored by the French navy, XBeach will be applied, with help of our group, to model swash motions and resulting morphological changes on the beach. Several members of the group have obtained beta versions.

Collaboration with USGS

The USGS at St Petersburg, Fl (Abby Sallenger and David Thompson) has been introduced to XBeach during a visit by Dirk-Jan Walstra and Jaap van Thiel de Vries and are planning to apply it to several of their datasets of hurricane impacts.

Incorporation in EU FP7 project

XBeach has been proposed as central model in a large EU 7th Framework Programme project, MICORE, about storm impacts on European coasts. Several members of this team will work with XBeach within that project, which is very likely to get EU approval based upon the exceptionally high score. Most members of our team will participate in this.

Collaboration with NOPP–CSTM project

The XBeach model has been presented to the NOPP – Community Sediment Transport Model project during the last May workshop in Woods Hole. Concepts from XBeach may be implemented into the ROMS-SED environment, whereas XBeach can profit from experiences in that group.

Collaboration with individual researchers

The following persons have expressed interest and have received software and documentation:

- Peter Ruggiero, Oregon State University
- Gerben Ruessink, Utrecht University
- Rui Tabora, University of Lisbon
- Jennifer Irish, Texas A&M University
- Sean Vitousek, University of Hawaii

Papers in preparation

Dano Roelvink, Ad Reniers, Ap van Dongeren, Jaap van Thiel de Vries, Jamie Lescinski, Dirk-Jan Walstra. Modelling of coastal processes under storm conditions, to be submitted to Coastal Engineering.

2.2   Implementation under LINUX

In order to run XBeach on Linux clusters, the code was compiled and tested using GNU g95 compiler and Intel compiler. In a number of routines, small modifications were made to overcome differences in strictness and initialization between compilers. The present code now runs smoothly under Linux as well as Windows.

2.3 Implementation of stationary wave solver

For applications under average conditions where swash and infragravity motions are less dominant, it can be useful to apply a stationary wave solver instead of the standard instationary one. If this solver only has to be run, say, every couple of minutes, a considerable time saving can be achieved. Therefore a forward-marching technique was implemented, where, starting from the sea boundary, wave conditions at each next grid line are solved iteratively until convergence is reached.

2.4 Incorporation of Beach Wizard assimilation with Argus data

In the framework of the ONR-sponsored project 'Beach Wizard', a method has been developed to assimilate Argus video data of wave dissipation, wave celerity and intertidal bathymetry with a wave model that predicts these quantities. This method has first been implemented in Delft3D, but with the present stationary wave solver this can be done much more efficiently. Therefore the assimilation scheme of Beach Wizard has been implemented within the XBeach model, and some preliminary tests have been carried out successfully.

References:

Anna Cohen, Ap van Dongeren, Dano Roelvink, Nathaniel Plant, Stefan Aarninkhof, Merrick Haller, Patricio Catalan. Nowcasting Of Coastal Processes Through Assimilation Of Model Computations And Remote Observations. Proc. ICCE San Diego, 2006

Ap van Dongeren, Nathaniel Plant, Anna Cohen, Dano Roelvink Merrick Haller and Patricio Catalan. Beach Wizard: Nearshore Bathymetry Estimation Through Assimilation Of Model Computations And Remote Observations. Paper subm. Coastal Engineering.

2.5 Implementation of space- and time-varying offshore boundary conditions

The Xbeach model is presently being expanded with functionality to account for surface elevation variations on the time scale of surges and tides, and for wave energy variations on the time-scale of wave groups (including associated bound wave surface elevations). The inputs on the boundary can be derived from larger area (flow) models such as Adcirc and from larger area wave models (such as SWAN or ST-WAVE).

We impose tidal (including surge) records on four corners of the domain. There can be multiple situations, namely a difference in tidal elevation on the seaward side and the bayward side of the barrier island, or a spatially uniform waterlevel, or a longshore gradient of the tidal elevation. These different situations are controlled with just a few parameters, which can be specified by the user.

We are imposing wave energy boundary conditions from 2D SWAN (for now) spectra or parameterized spectra on the seaward side of the domain following Van Dongeren et al. JGR 2003). Along this boundary we may have more than one spectrum (longshore variation) for which we account using a masking technique cf. Groeneweg et al. ICCE 2004). These functionalities are presently being implemented and are in the testing phase.

2.6   Updated wave current interaction modeling

The interaction of waves and currents has been reformulated to obtain a more robust description during the extreme conditions that are encountered during severe storm conditions. Starting with the wave action balance given by:

$$\frac{\partial A}{\partial t} + \frac{\partial c_x A}{\partial x} + \frac{\partial c_y A}{\partial y} + \frac{\partial c_\theta A}{\partial \theta} = -\frac{D}{\sigma}$$

with the wave action:

$$A(x, y, \theta) = \frac{S_w(x, y, \theta)}{\sigma(x, y)}$$

where S_w represents the wave energy in each directional bin and σ the intrinsic wave frequency. The wave action propagation speeds in x- and y-direction are given by:

$$c_x(x, y, \theta) = c_g(x, y)\cos(\theta) + u(x, y) \cdot \min\left(1.0, \frac{h}{h_{wci}}\right)$$

$$c_y(x, y, \theta) = c_g(x, y)\sin(\theta) + v(x, y) \cdot \min\left(1.0, \frac{h}{h_{wci}}\right)$$

where θ represents the angle of incidence with respect to the x-axis and h represents the minimum depth at which wave current interaction is still fully accounted for. For smaller depths a linear decay is used. Effectively this means that close to the water line wave current interaction is reduced. The propagation speed in θ-space is obtained from:

$$c_\theta(x,y,\theta) = \frac{\sigma}{\sinh 2kh}\left(\frac{\partial h}{\partial x}\sin\theta - \frac{\partial h}{\partial y}\cos\theta\right) + \cos\theta\left(\sin\theta\frac{\partial u}{\partial x} - \cos\theta\frac{\partial u}{\partial y}\right) + \sin\theta\left(\sin\theta\frac{\partial v}{\partial x} - \cos\theta\frac{\partial v}{\partial y}\right)$$

taking into account bottom refraction (first term on the RHS) and current refraction (last two terms on the RHS). The wave number k is obtained from the eikonal equations (e.g. Dingemans, 1993):

$$\frac{\partial k_x}{\partial t} + \frac{\partial \omega}{\partial x} = -\bar{c}_y\left(\frac{\partial k_y}{\partial x} - \frac{\partial k_x}{\partial y}\right)$$

$$\frac{\partial k_y}{\partial t} + \frac{\partial \omega}{\partial y} = \bar{c}_x\left(\frac{\partial k_y}{\partial x} - \frac{\partial k_x}{\partial y}\right)$$

where the subscripts refer to the direction of the wave vector components and ω represents the absolute radial frequency. The RHS of the eikonal equations ensures the irrotationality of wave number vector field (pers. Comm. RJ Labeur, Delft University of Technology). The wave number is the obtained from:

$$k = \sqrt{k_x^2 + k_y^2}$$

The absolute radial frequency is given by:

$$\omega = \sigma + \vec{k}\bullet\vec{u}$$

and the intrinsic frequency is obtained from the linear dispersion relation:

$$\sigma = \sqrt{gk\tanh kh}$$

The group velocity is obtained from linear wave theory:

$$c_g = nc = \left(\frac{1}{2} + \frac{kh}{\sinh 2kh}\right)\frac{\sigma}{k}$$

This concludes the advection of wave action.

To test the wave current interaction a numerical rip-current experiment is performed. The root mean square incident wave height at the offshore boundary is 1 m, with a mean wave period of 5 s, normally incident on the rip-channelled beach. The rip-channel configuration is similar to the rip-channels found in Monterey Bay (Reniers et al., 2007). The case without wave current interaction shows a strong rip current exiting the rip channel. This rip current is highly unstable

due to its strong velocity shear (Yu and Slinn, 2003; Haller and Dalrymple, 2001) resulting in local vortices that are transported offshore by the rip current flow. Including wave current interaction limits the offshore extent of the rip current considerably (compare panels in Figure below). The rip current flow is still unstable but the instabilities now occur within the surfzone resulting in a strong eddy circulation. It must be noted that the turbulent eddy viscosity has been ignored in the present computations. Inclusion of the turbulent eddy viscosity again stabilizes the flow further. An increased wave height is observed within the rip-channel at locations of opposing currents, consistent with results of Yu and Slinn [2003] and Reniers et al. [2007].
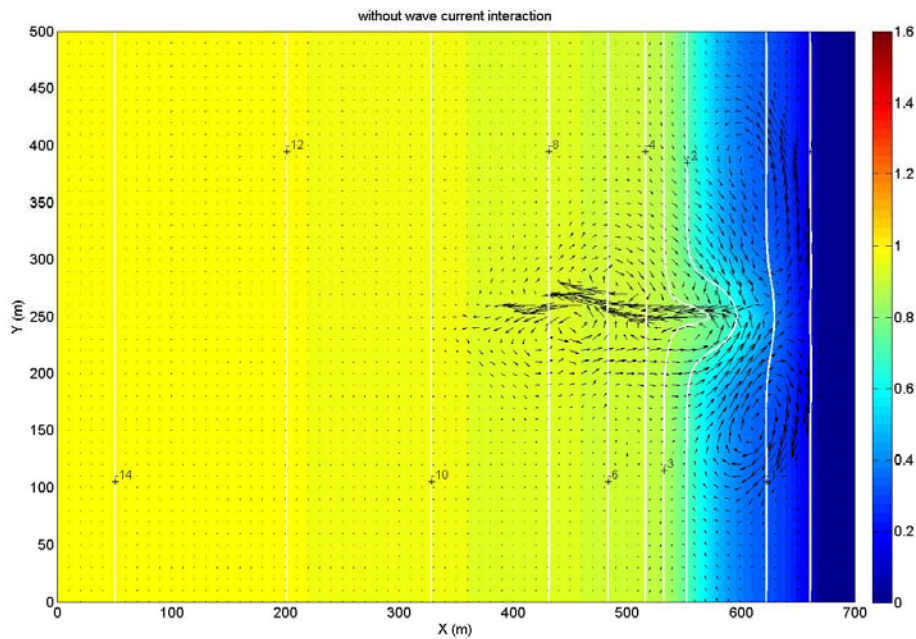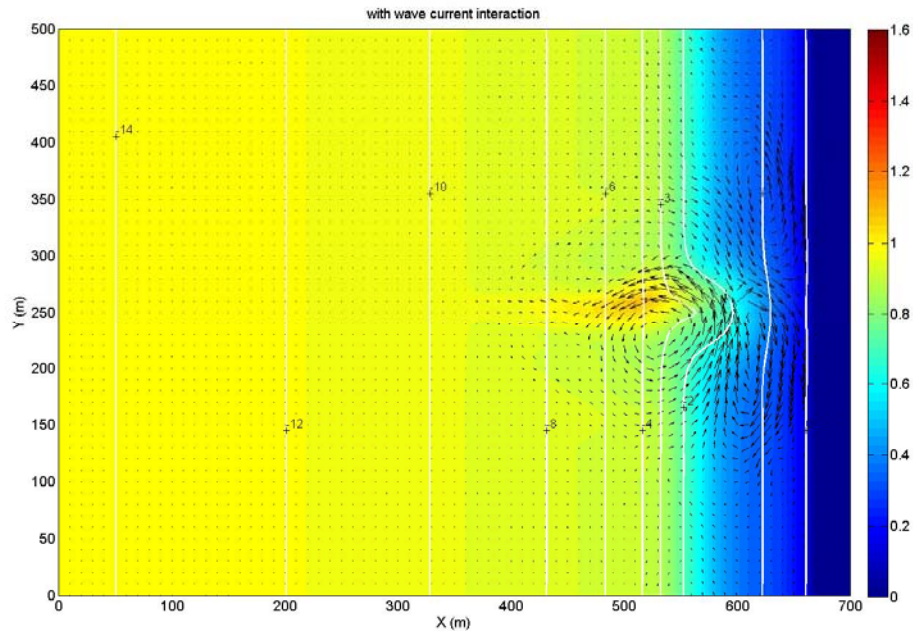
Figure Upper panel: Snapshot of the root mean square wave height (indicated by the colour bar in m) and corresponding velocity field (arrows indicate direction and magnitude) **without** wave current interaction. Lower panel: Similar but **with** wave current interaction.

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Haller, M.C., and D.A. Dalrymple: Rip current instabilities, J. *Fluid Mech., 433*, 161-192, 2001.

Reniers A. J. H. M., J. H. MacMahan, E. B. Thornton and T. P Stanton, Modeling of very low frequency motions during RIPEX, *J. Geophys. Res., 112*, C07013, doi:10.1029/2005JC003122, 2007.

Yu, J. and D.N. Slinn: Effects of wave-current interaction on rip currents, *J. Geophys. Res., 108*, 3088, doi:10.1029/2001JC001105, 2003

2.7   Modeling large scale dune erosion tests to study the effect of the wave period on dune erosion

Large scale dune erosion experiments conducted in the Delta flume of Delft Hydraulics revealed that the wave period has a significant influence on the amount of dune erosion. A 50% increase of the wave period resulted in 24% more erosion for normative surge conditions in the Netherlands. In this section collected measurements are used to study the effect of the wave period on dune erosion within the XBeach model.

Flume experiments

Five dune erosion tests in the flume were simulated with the XBeach model. The hydrodynamic boundary conditions for each test varied and are listed in Table 1. Tests T01, T02 and T03 were set up to provide insight into the effect of the wave period on dune erosion. The wave period was the only parameter that varied in these tests. The wave conditions in Tests T01, T02 and T03 correspond to peak wave periods in a prototype situation of T_p = 12 s, T_p = 15 s and T_p = 18 s respectively, and to a prototype wave height of H_s = 9 m. The still water level was fixed at 4.5 meter in the flume near the wave board (for all tests) and corresponds to the maximum normative storm surge level for the Dutch situation. In Test T04 a different initial cross-shore profile was used with wave and surge conditions as in Test T03 (see later in Figure 3). A Pierson-Moskowitz wave spectrum was applied in Tests T01 to T04. Tests DP01 was carried out with a double-peaked wave spectrum. The duration of a test was at least six hours and tests were divided into intervals (A-E). After each interval the tests were interrupted at 0.10, 0.30, 1.00, 2.04 and 6.00 hours to carry out profile measurements.

Test	Interval	H_{m0} [m]	T_p [s]	$T_{m-1,0}$ [s]	SWL [m]	Spectrum shape
T01	A-E	1.50	4.90	4.45	4.50	Pierson-Moskowitz
T02	A-E	1.50	6.12	5.56	4.50	Pierson-Moskowitz
T03	A-E	1.50	7.35	6.68	4.50	Pierson-Moskowitz
T04	A-E	1.50	7.35	6.68	4.50	Pierson-Moskowitz
DP01	A-E	1.50	6.12	3.91	4.50	Double peaked

Table 1 Simulated flume experiments with the XBeach model.

XBeach simulations

All simulations were carried out on the same grid and with the same numerical settings. An XBeach input file for test T01 is enclosed in Appendix 3. Prior to each simulation the wave dissipation formulation (Roelvink 1993) was calibrated (see Table 2).

Test	α	γ	n
T01	1.0	0.55	10
T02	1.0	0.5	10
T03	1.0	0.5	10
T04	1.0	0.5	10
DP01	1.0	0.60	10

Table 2 Parameter settings for calibrated wave dissipation model

Model results for test T01, T02 and T03 are compared in Figure 1. Detailed comparison of measured and simulated wave transformation, hydrodynamics, sediment concentrations and profile evolution is found in Appendix 4. The wave period effect on dune erosion is simulated well with the XBeach model. The simulated position of the dune crest is computed a bit too far landward which is mainly explained by the relative small resolution of the grid near the dune face. Measured and simulated profiles compare well except from some details. The measured profile shows a small bar around x = 185 meter, which is not predicted by the XBeach model. Also the bed slopes from XBeach in this area are much gentler than observed in the measured profiles. The evolution of measured and simulated erosion volumes with progress of a test show comparable trends.
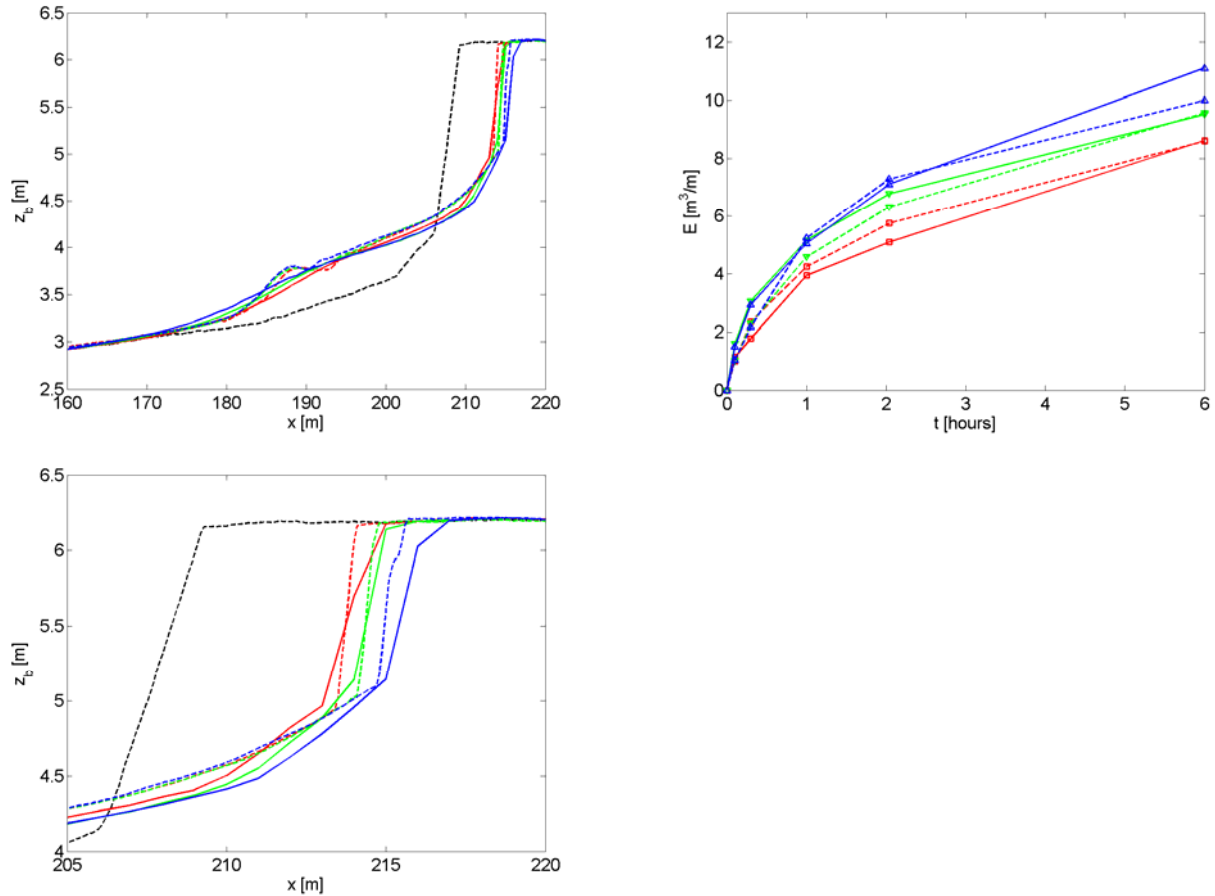
Figure1 Left panel: Development of measured (dashed lines) and simulated (solid lines) profiles after six hours for test T01 (red), T02 (green) and test T03 (blue). Right panel: Development of measured (dashed lines) and simulated (solid lines) erosion volumes with progress of test T01 (red), T02 (green) and test T03 (blue) at the end of interval A,B,C,D and E.

Simulations results for test DP01 with a double peaked spectrum are shown in Figure 2. The XBeach model underestimates the amount of dune erosion for this test. Though the position of the dune crest is predicted well comparison of measured bathymetries and erosion volumes clearly show that the dune erosion is underestimated by the model. A possible explanation may be found in the characteristic wave period that was used in the simulation and which was set as the spectral mean wave period $T_{m-1,0}$ (as in the other tests). It is questionable however whether this wave period is most suitable to describe a double peaked spectrum.
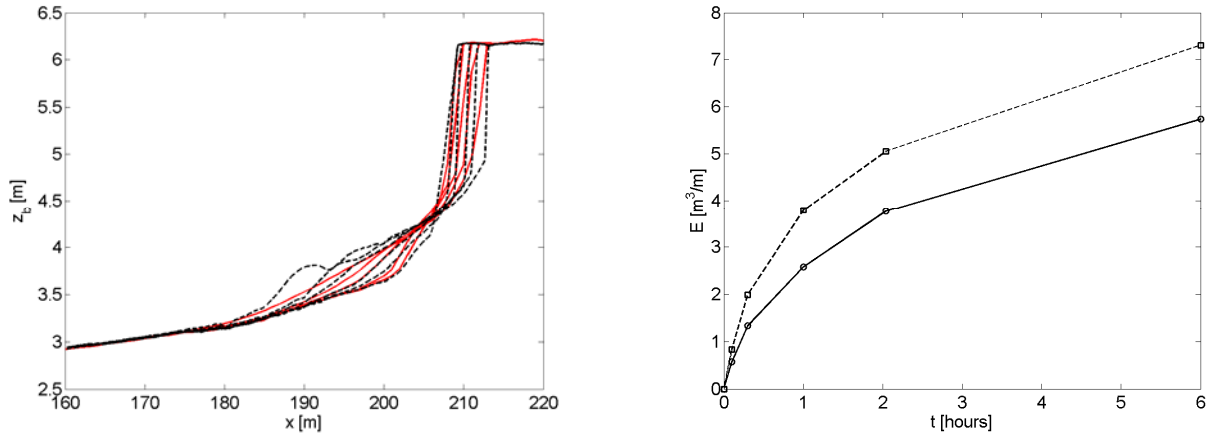
Figure 2 Left panel: Measured (dashed lines) and simulated (solid lines) profiles for test DP01 at the end of interval A,B,C,D and E. Right panel: Development of measured (dashed line) and simulated (solid line) erosion volumes with progress of test DP01 at the end of interval A,B,C,D and E.

Simulation results for test T08 with a different initial profile are shown in Figure 3. The XBeach model overestimates the amount of dune erosion for this test and the position of the dune crest is located too far landward. Despite that the average erosion rate is overestimated by the model; qualitatively the same developments are simulated as in the physical model test. The small dune is eroded till it reaches a critical width after which over wash takes place. Sand is deposited in the trough between the two dunes around $x = 215$ meter which was also observed during the measurements.
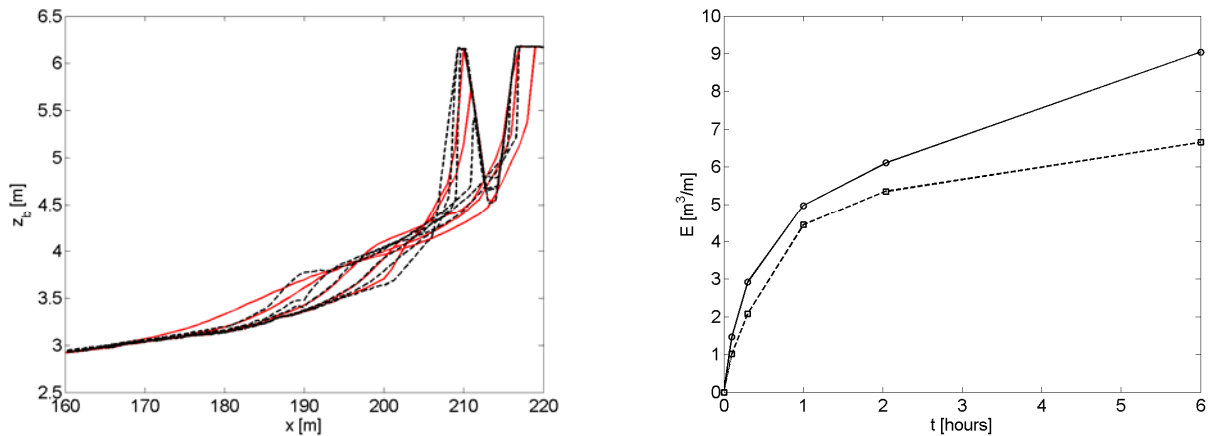
Figure 3 Left panel: Measured (dashed lines) and simulated (solid lines) profiles for test T04 at the end of interval A,B,C,D and E. Right panel: Development of measured (dashed line) and simulated (solid line) erosion volumes with progress of test T04 at the end of interval A,B,C,D and E.

3   Plans for coming period

For the coming period we plan the following activities:

- Implementing space- and timevarying boundary conditions
- Assisting in testing by ERDC and others
- Implementing non-uniform grid size to speed up computations
- Investigating possibilities of parallellization
- Testing against data for Monterey Bay, in collaboration with Univ. of Miami and Naval Postgraduate School
- Testing against Duck data
- Presenting results at Oahu workshop (D. Roelvink) and participating in Morphos meeting (D. Roelvink and A. van Dongeren)
- Preparation of papers.
- Development/adaptation of test bed

Appendix 1 Abstract 10th International Workshop on Wave Hindcasting & Forecasting & Coastal Hazard Assessment

Modeling hurricane impacts on beaches, dunes and barrier islands

Dano Roelvink[1,2,3], Ad Reniers[,3,4], Ap van Dongeren[2], Jaap van Thiel de Vries[2,3], Jamie Lescinski[2], Dirk-Jan Walstra[2,3]

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The devastating effects of hurricanes on low-lying sandy coasts, especially during the 2004 and 2005 seasons have pointed at an urgent need to be able to assess the vulnerability of coastal areas and (re-)design coastal protection for future events, but also to evaluate the performance of existing coastal protection projects compared to 'do-nothing' scenarios.

In order to address such questions the Morphos-3D project was initiated. This project brings together models, modelers and data on hurricane winds, storm surges, wave generation and nearshore processes (wave breaking, surf and swash zone processes, dune erosion, overwashing and breaching). For modeling the nearshore processes a new public domain model, 'XBeach', was developed and will continue to be validated and improved.

The XBeach model can be used as stand-alone model for small-scale (project-scale) coastal applications, but will also be used within the Morphos model system, where it will be driven by boundary conditions provided by the wind, wave and surge models and its main output to be transferred back will be the time-varying bathymetry and possibly discharges over breached barrier island sections.

The model solves coupled 2DH equations for wave propagation, flow, sediment transport and bottom changes, for varying (spectral) wave and flow boundary conditions. It resolves the wave-group and infragravity time scales, which are responsible for most of the swash and overwash motions, which thus can be modeled explicitly. The model has already been validated against extensive large-scale flume data sets including short and long wave dirstributions, return flow, orbital velocities, concentrations and profile change during dune erosion events. An essential part is an avalanching mechanism which allows a surprisingly accurate description of the evolution of the upper profile and dune face.

Next steps that will be reported at the workshop include field validation for hurricane impacts ranging from dune scarping to full breaching.
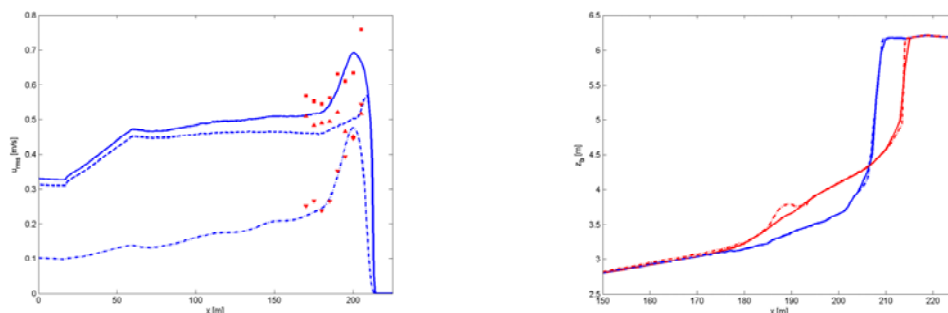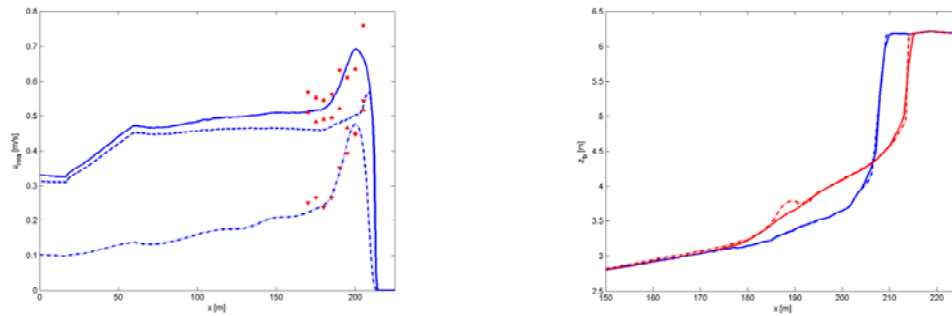

Figure 1. Left: measured and computed LF, HF and total rms orbital velocities ; Right: Initial (blue), measured (red dashed) and computed (red drawn) profile evolution for large-scale dune erosion test.

Appendix 2 Abstract ICCE 2008

Abstract no 655

Modeling hurricane impacts on beaches, dunes and barrier islands

Dano Roelvink[1,2,3], Ad Reniers,[3,4], Ap van Dongeren[2], Jaap van Thiel de Vries[2,3], Jamie Lescinski[2], Dirk-Jan Walstra[2,3]

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Introduction

The devastating effects of hurricanes on low-lying sandy coasts, especially during the 2004 and 2005 seasons have pointed at an urgent need to be able to assess the vulnerability of coastal areas and (re-)design coastal protection for future events, but also to evaluate the performance of existing coastal protection projects compared to 'do-nothing' scenarios.

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The XBeach model can be used as stand-alone model for small-scale (project-scale) coastal applications, but will also be used within the Morphos model system, where it will be driven by boundary conditions provided by the wind, wave and surge models and its main output to be transferred back will be the time-varying bathymetry and possibly discharges over breached barrier island sections.

Model formulations

The model solves coupled 2DH equations for wave propagation, flow, sediment transport and bottom changes, for varying (spectral) wave and flow boundary conditions. It resolves the wave-group and infragravity time scales, which are responsible for most of the swash and overwash motions, which thus can be modeled explicitly.

The wave model is based on the time-varying wave action balance for the incident waves, which are assumed to be narrow banded in frequency but with finite directional spreading:

$$\frac{\partial A}{\partial t} + \frac{\partial c_x A}{\partial x} + \frac{\partial c_y A}{\partial y} + \frac{\partial c_\theta A}{\partial \theta} = -\frac{D}{\sigma} \tag{1}$$

This equation describes the propagation and dissipation (D) of wave groups with a dominant frequency σ and time-varying wave action A. The wave groups propagate with group velocity c_x, c_y; refraction is represented as propagation in θ-space where θ is the wave direction. The time- and space varying wave dissipation feeds into a roller energy balance equation; together the wave action and roller energy dissipation provide the time- and space varying forcing that drives the 2DH shallow water equations. The setup is similar to that reported in Reniers et al (2004) but does not require an external wave driver and allows wave groups with different directions to cross each other.

The model has already been validated against extensive large-scale flume data sets including short and long wave distributions, return flow, orbital velocities, concentrations and profile change during dune erosion events (Fig. 1). An essential part is an avalanching mechanism which allows a surprisingly accurate description of the evolution of the upper profile and dune face.

Figure 1. Left: measured and computed LF, HF and total rms orbital velocities ; Right: Initial (blue), measured (red dashed) and computed (red drawn) profile evolution for large-scale dune erosion test.

In Figure 2 a principle test example is shown whereby the same dune profile is narrowed and the crest lowered by 0.5 m, allowing the scarping of the dune face to change into overwashing and eventually full breaching. Note how before overwashing the sand is mainly transported offshore, whereas after overwashing the dominant direction is onshore.
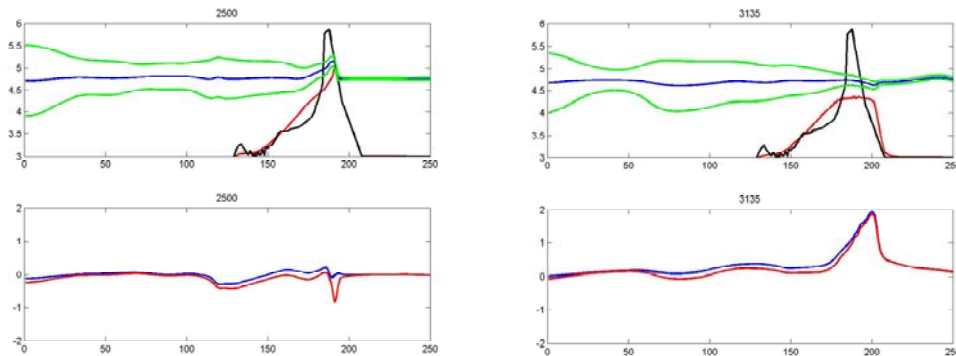
Figure 2. Snapshots of principle test of overwashing.
Left panels: just before overtopping; right panels: full breaching. Top panels: initial profile (black), short wave envelope (green), low-frequency water elevation (blue) and actual profile (red). Bottom panels: LF velocity including (red) and excluding (blue) wave-induced return flow.

Next steps that will be reported at the conference include field validation for hurricane impacts in 1D cross-shore and full 2D applications, for conditions ranging from dune scarping to full breaching.

References
Reniers, A.J.H.M., J.A. Roelvink and E.B. Thornton. (2004). Morphodynamic modelling of an embayed beach under wave group forcing. J. of Geophysical Res. , VOL. 109, C01030, doi:10.1029/2002JC001586, 2004

Appendix 3: XBeach input file

grid input
nx = 184
ny = 2
dx = 1.0
dy = 5
xori = 14.
yori = 0.
alfa = 0.
depfile = T06.dep
posdwn = -1

wave input
break = 1
Hrms = 1.02
Tm01 = 4.45
dir0 = 270.
m = 1024
nt = 12000
hmin = 0.3
Tlong = 31.2
gamma = 0.55
alpha = 1.
delta = 0.0
n = 10.
rho = 1000
g = 9.81
thetamin = -5.
thetamax = 4.
dtheta = 2.
wci = 0
instat = 3
nuh = 0
roller = 1
beta = 0.1
refl = 1

flow input
C = 65.
eps = 0.01
umin = 0.1
zs0 = 4.5
tstart = 100
tint = 1.
tstop = 2260
CFL = 0.2

sed input
A = 0.002
dico = 1.
D50 = 0.0002
D90 = 0.0003
rhos = 2650
morfac = 10
morstart = 100
por = 0.4
dryslp = 1.0
wetslp = 0.15
hswitch = 0.1

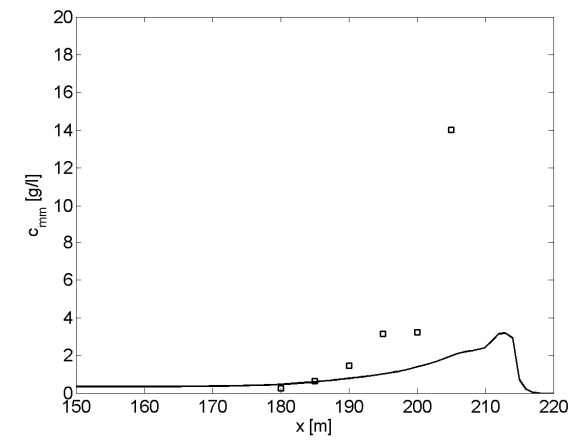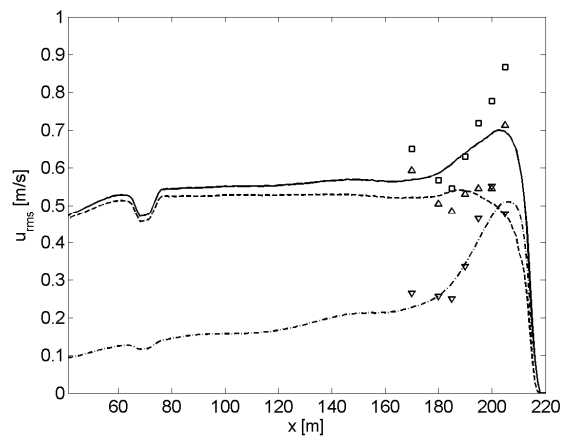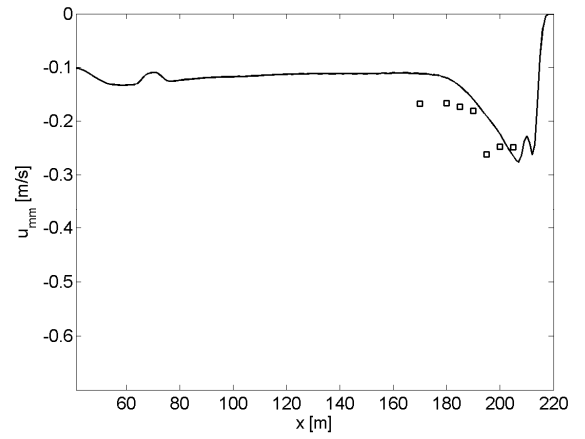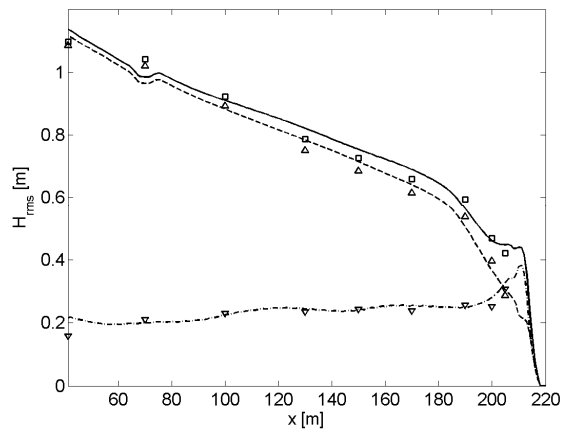## Appendix 4: Detailed comparison simulation results with measurements

3 – 1
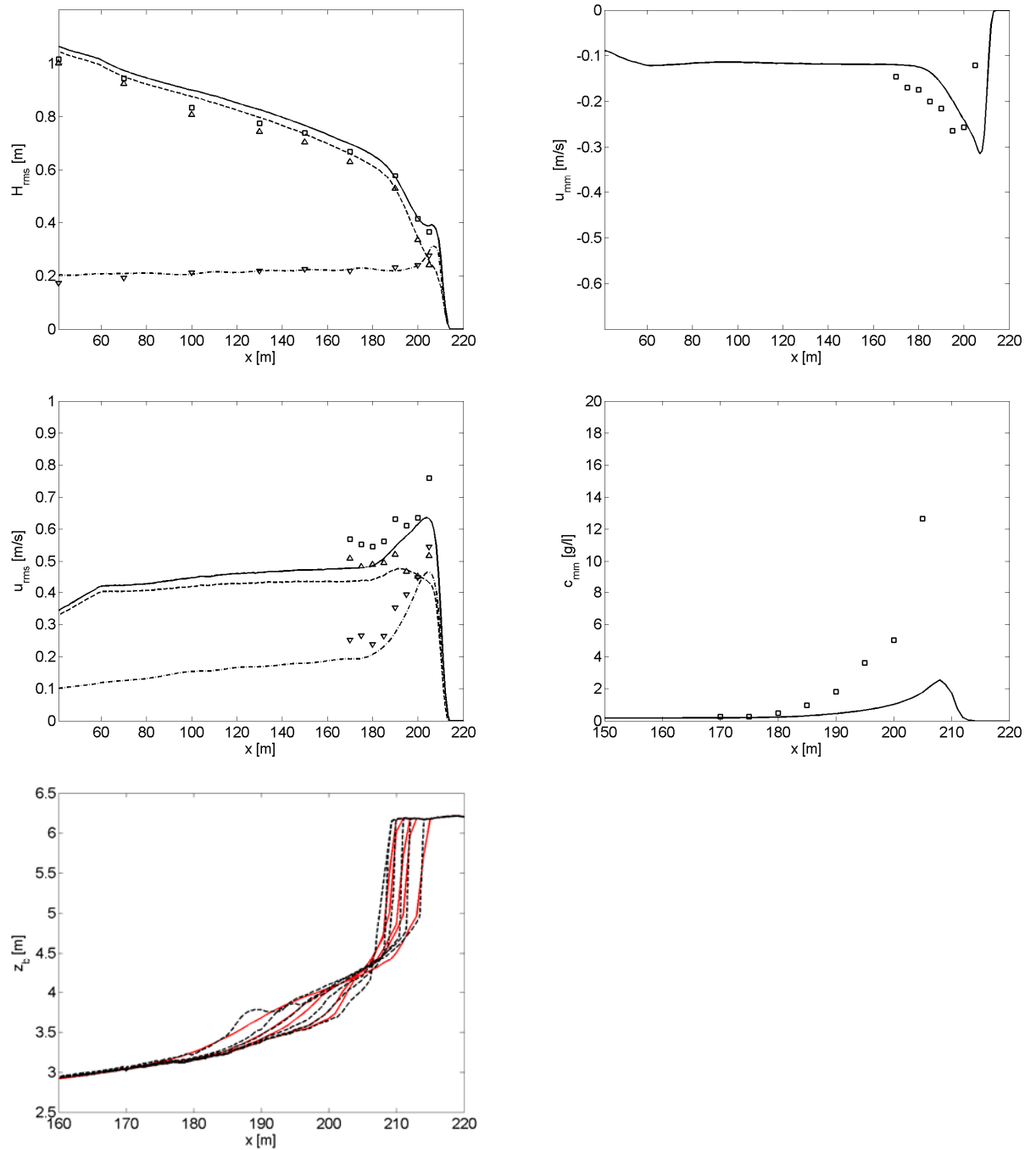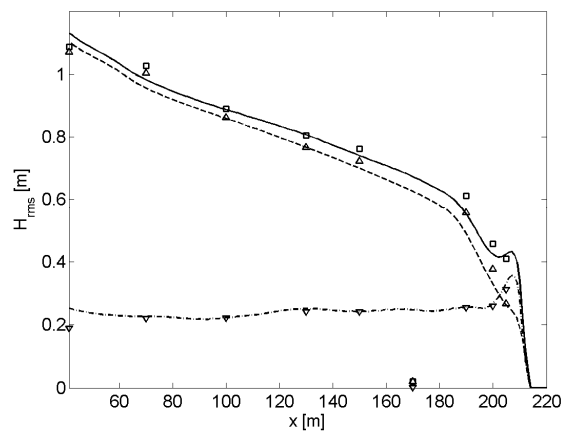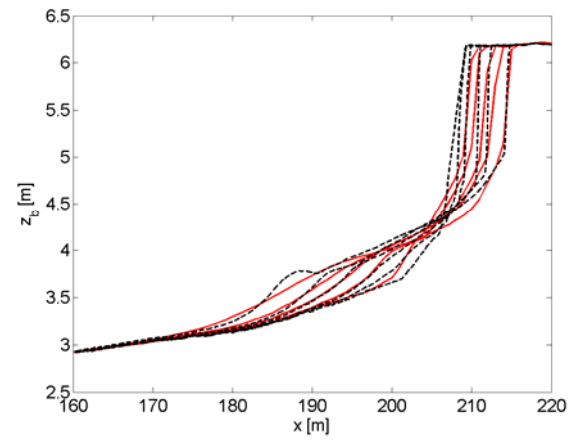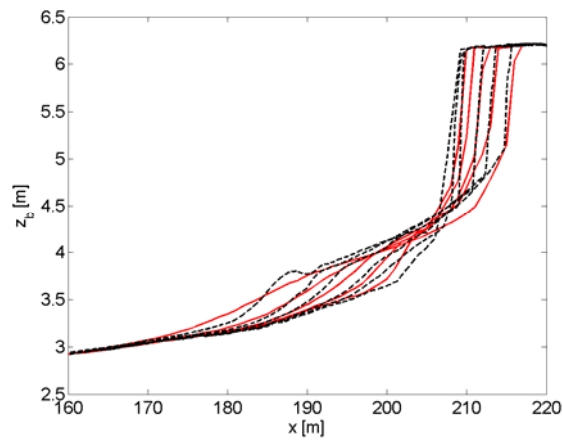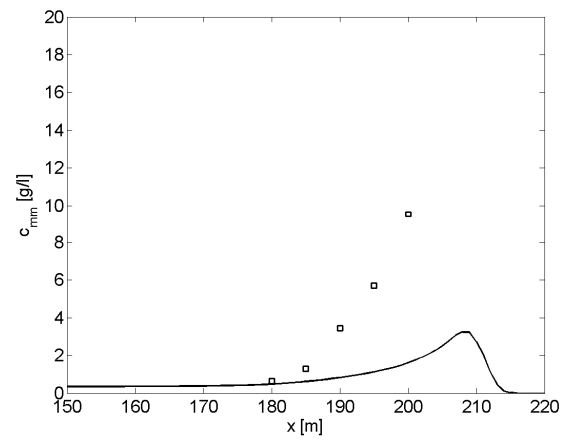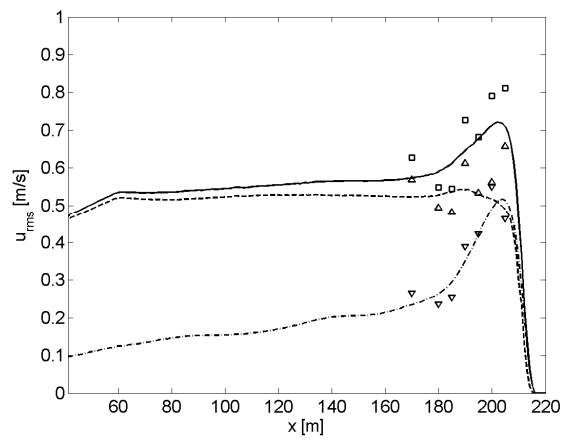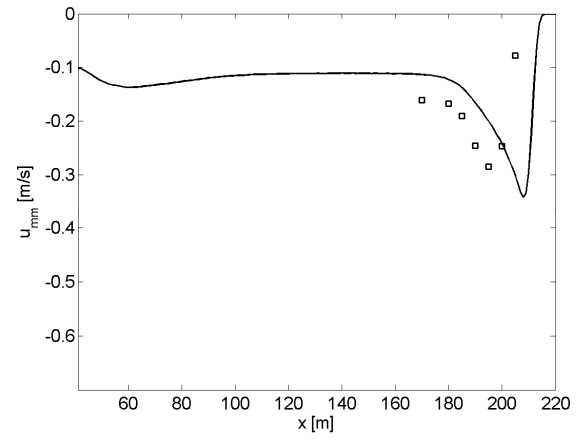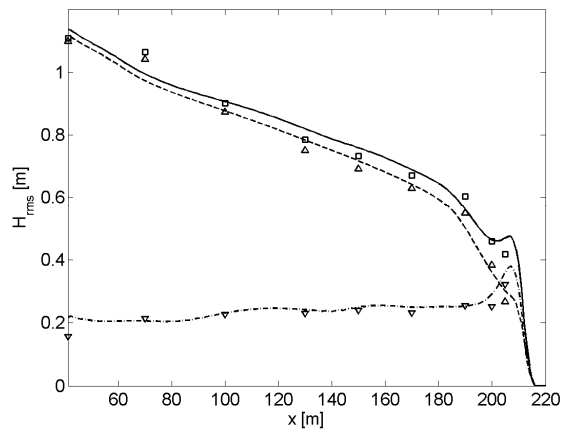
Test T01

Test T02

Test T03

Test DP01

Test T08